# Time variability and heterogeneity in the coma of 67P/Churyumov-Gerasimenko

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**Abstract**: Comets contain the best-preserved material from the very beginning of our planetary system. Their nuclei and comae composition reveal clues about physical and chemical conditions during the early Solar system when comets formed. ROSINA/DFMS (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis / Double Focusing Mass Spectrometer) onboard the Rosetta spacecraft has measured the coma composition of comet 67P/Churyumov-Gerasimenko (67P) with excellent time resolution and compositional detail. Measurements were made over many comet rotation periods and a wide range of latitudes. These measurements show large fluctuations in composition in a heterogeneous coma that has diurnal and possibly seasonal variations in the major outgassing species: $H_2O$, CO, and $CO_2$. These results indicate a complex coma-nucleus relationship where seasonal variations may be driven by temperature differences near the comet surface.

**One Sentence Summary:** ROSINA/DFMS shows that 67P/Churyumov-Gerasimenko has a highly heterogeneous coma with large diurnal and possibly seasonal variations.

**Main Text:** Initially, comets were assumed to be homogeneous in structure and were classified depending on the location where they formed in the protoplanetary disc *(1-4)*. This classification implied a homogenous composition of the nucleus within a given formation location. The nucleus composition has not been sampled directly. Rather, it is implicitly assumed that measurements of the outgassing of comets reveal the composition of the volatile components of the nucleus. Compositional homogeneity of at least one comet was confirmed by studying outgassing from the fragments of the broken up comet Schwassmann-Wachmann 3 *(5)*. Detailed observations of other cometary comae indicated that there was some evidence of heterogeneity. Missions to comet Halley detected multiple jet-like features, revealing an asymmetric inner coma. The release of volatiles was dominant on the sunlit surface of the nucleus *(6, 7).* Distribution asymmetries in composition in the coma of Tempel 1 with the Deep Impact mission *(8)* indicated compositional differences in the inner coma of the comet. These remote sensing observations at Tempel 1 indicated an absence of correlation between $H_2O$ and $CO_2$ in the coma.

Detailed, close up cometary images also showed visible differences between different areas of cometary nuclei. These images suggested that heterogeneity in the coma of a comet may be related to heterogeneity of the nucleus. Observations by EPOXI at Hartley 2 in 2010 near perihelion indicated that the nucleus is complex, with two different sized lobes separated by a middle waist region that is smoother and lighter in color *(9)*. Outgassing from sunlit surfaces of the nucleus revealed that the waist and one of the lobes were very active. A $CO_2$ source was detected at the small lobe of the comet, while the waist was more active in $H_2O$ and had a significantly lower $CO_2$ content. Based on these coma observations, it has been tentatively suggested that the heterogeneity in the comet's nucleus was primordial *(9)*. Seasonal effects could not be ruled out because the observations also showed a complex rotational state for the comet *(9).* The smaller of the two lobes may have had a different illumination because of this complex rotation *(9).*

In support of the findings at Hartley 2, there are indications of a heterogeneous nucleus for comet Tuttle and, separately, a heterogeneous coma *(9, 10).* The Stardust mission to comet P81/Wild 2, on the other hand, showed a large mixing of materials on the scale of grains and therefore a homogenized mix of the refractory material in the comet *(11).* These results and the results at Hartley 2 raise the larger question whether heterogeneity in the coma is a common feature in comets and whether this heterogeneity reveals an underlying heterogeneity in the composition of the nucleus. Such heterogeneity would point to general transport of cometesimals in the early Solar System.

In August, the European Space Agency's mission Rosetta arrived at its target comet 67P after a ten-year journey (*12).* Rosetta provides the excellent opportunity for long-term study during the comet's sunward approach to and through perihelion. The observations presented here are from the two-month period starting near the initial encounter at about 3.5 AU from the Sun.
Like Hartley 2, the nucleus of 67P appears complex in shape. 67P consists of two lobes of different sizes, connected by a neck region. The lobes are much larger, more rugged, and darker than the neck region and the overall shape has been described as a rubber duck (*13*). The structural similarities of 67P and Hartley 2 open the possibility of investigating another possibly heterogeneous comet and, by virtue of the extended observations at 67P, determining if heterogeneity in the coma and nucleus are related.

Here we show compositional variations in $H_2O$, CO, and $CO_2$ at comet 67P observed with ROSINA/DFMS *(14).*

During Rosetta's approach to 67P, ROSINA/DFMS measured the coma composition with a time resolution much better (>10 measurements) than the rotation period of the comet. In August, the spacecraft scanned the comet at positive latitudes (summer hemisphere) from about 10º up to almost 90º (latitude and longitude from the OSIRIS shape model). In September, the spacecraft made a similar scan at negative latitudes (winter hemisphere) down to about -50º. Here, we present two 4-day periods from these two scans in August and September to illustrate the diurnal and latitudinal variations and heterogeneity of the cometary coma.
Figure 1 shows the first 4-day period from August 4 to 8, 2014. The upper panel shows the counts on the DFMS detector for $H_2O$, CO, and $CO_2$ and the lower panel shows the latitude and longitude of the nadir view of the spacecraft. At the top is the distance from the spacecraft to the comet.
During this approach and latitude scan, the $H_2O$, CO, and $CO_2$ signals from the comet increased by more than an order of magnitude, roughly in agreement with a $1/R^2$ dependence on the coma density, with R the cometocentric distance. Overall, the $H_2O$ signal is the highest; however, there are clearly periods when the CO or $CO_2$ signals rival that of $H_2O$ [derivation of relative concentrations in Supplementary Material].
Superposed on this general increase in signal are large, diurnal variations for all three species. For $H_2O$, these variations are periodic, initially with half the rotation rate of the comet (~6.2 hours) and then, after August 6, at the rotation rate (~12.4 hours). Peaks occur at ±90º longitude.

For the most part, CO follows the $H_2O$ signal, but the variations are smaller. $CO_2$ shows a different periodicity. Initially, a $CO_2$ peak is observed in association with an $H_2O$ peak at 90º longitude and a second $CO_2$ peak occurs approximately 3 hours later at about -45º longitude. After August 6, a single $CO_2$ peak is observed; however, this peak is not coincident with the $H_2O$ peak. After August 6, the single $CO_2$ peak occurs between about 0º and 45º longitude.
Figure 2 shows the second 4-day period from September 15 to 19, 2014. The format is the same as in Figure 1. Over this 4-day period, the spacecraft remained at a nearly fixed distance from the comet and executed a southern latitude scan from about 0º to -45º latitude.
The diurnal variations seen in Figure 1 are also observed at southern latitudes in Figure 2. The $H_2O$ peaks at half the rotation rate of the comet are nearly equal and there is a deep minimum between the two peaks. As in Figure 1, CO follows $H_2O$. However, there is much less variation in CO than in $H_2O$, resulting in times when the CO signal is greater than that for $H_2O$. The $CO_2$ peaks occur at about +90º and -45º longitude as was observed in Figure 1 at positive latitudes. The best example of the differences between $H_2O$ and $CO_2$ are seen just after September 18. The nearly equal $H_2O$ peaks and the deep minimum in the $H_2O$ signal are evident as is the clear offset between the second $CO_2$ and $H_2O$ peaks.
In Figure 3, we use the time period from September 18 to 19, 2014 to illustrate the different views of the comet when the peaks occur. The lower part of Figure 3 shows the spacecraft views of the comet. The Sun is shining on the comet from the top middle of the pictures. The peaks in $H_2O$ signal are observed when the neck of the comet is in view of the spacecraft. The deep minimum in $H_2O$ signal is observed when the spacecraft views the southern hemisphere of the larger of the two lobes. This large lobe blocks a direct view of the neck of the comet. The separate, second $CO_2$ enhancement is observed when the spacecraft views the "bottom" of the larger of the two lobes of the comet. The CO signal in the second rotation of the comet follows the $CO_2$ profile and, CO and $CO_2$ have very similar intensities.

Figures 1 through 3 demonstrate that the coma of 67P is highly heterogeneous. $H_2O$, CO, and $CO_2$ variations are strongly tied to the rotation period of the comet and the observing latitude. At high negative latitudes, the $H_2O$ signal varies by at least two orders of magnitude (Figure 3). The deep minimum occurs when the larger of the two lobes of the comet effectively blocks the neck region. Since this blockage is not as effective when the spacecraft faces the other, smaller lobe, the minimum is not as deep (see Figure 3). Also, the $H_2O$ minima are not as deep when the spacecraft is at mid and high positive latitudes because there is a view of the neck region over the edge of the larger lobe (see Figure 1 and the observations on Sept 15 in Figure 2).
The separate $CO_2$ peak also occurs when the spacecraft views the bottom of the larger of the two lobes of the comet (see Figure 3 at 5 hours). This peak occurs systematically at about -45º longitude independent of latitude, except at high positive latitudes. CO variations are not as large. CO follows $H_2O$ at positive latitudes and follows both $H_2O$ and $CO_2$ at negative latitudes. The separate $CO_2$ peak, the large variations in the $H_2O$ signal, and the weaker variations in CO result in large changes in the CO and $CO_2$ concentration in the heterogeneous coma of 67P. For example, the $CO/H_2O$ number density ratio is $0.13\pm0.07$ and the $CO_2/H_2O$ ratio is $0.08\pm0.05$ in the last $H_2O$ peak on August 7 at 18 hours in Figure 1 (measured high in the summer hemisphere). However, The $CO/H_2O$ ratio changes from 0.56±015 to $4\pm1$ and back to $0.38\pm0.15$ within the second cometary rotation in Figure 3 occurring between 12 and 24 h on September 18 (measured low in the winter hemisphere). Similarly, the $CO_2/H_2O$ ratio changes from $0.67\pm0.15$

to 8±2 and back to 0.39±0.15 over the same rotation. These are very large changes within a short amount of time, indicating a strongly heterogeneous and time variable coma.

The similarities in the structure of the nuclei and the heterogeneous comae of 67P and Hartley 2 are striking. The behavior in terms of the $H_2O$ dominant outgassing at the neck versus $CO_2$ outgassing at one of the lobes described here was also found for Hartley 2.

The compositional differences in the Hartley 2 coma were interpreted as evidence for a heterogeneous cometary nucleus (*9*). However, seasonal effects could not be ruled out. With observations over a wide range of latitudes at 67P, we can distinguish compositional differences and seasonal effects. Figure 4 shows the $CO_2/H_2O$ density ratio from August 17 through September 22 mapped onto the shape model.

Although a direct mapping of the signal observed in the coma is oversimplified, generalized interpretation of the mapping reveals features of the outgassing of the comet. Seasonal effects on the $CO_2/H_2O$ ratio are clearly evident in this mapping in Figure 4. On the upper half of the comet, the $CO_2/H_2O$ ratio is less than 1, indicating a higher sublimation of $H_2O$ from positive latitude regions that receive more illumination during northern hemisphere summer on the comet. A broad region of high $CO_2/H_2O$ ratio occurs at negative latitudes in the winter hemisphere. The high ratio is the result of deep minima in the $H_2O$ signal such as the one shown in Figure 3 on September 18 at 4 hours. This region of the comet being in winter hemisphere is poorly illuminated by the Sun. With limited illumination, this region of the comet nucleus may be significantly colder than other regions, including the neck and smaller lobe. The temperature at and below the surface of the nucleus may be sufficient to sublimate CO and $CO_2$, but not sufficient to sublimate water. The weak, periodic illumination of this region in Figure 4 may be sufficient to drive CO and $CO_2$ sublimation, producing the separate CO and $CO_2$ peak in Figure 3 at 18 hours. Thus, Figure 4 suggests that the strong heterogeneity in the coma of comet 67P is driven by seasonal effects on the comet nucleus. At this stage we have no clear indication of a heterogeneous nucleus. However, the smaller variation of CO and $CO_2$ compared to $H_2O$ might indicate that CO and $CO_2$ sublimates from some depth, while H2O sublimates closer to the surface and experiences more direct temperature differences due to sunlight. Furthermore, that there is no overall correlation between $H_2O$, CO and $CO_2$ leads to the conclusion that the three molecules are not correlated in outgassing or CO and $CO_2$ are not embedded in $H_2O$. For Temple 1 layering of material was found and supports the above idea (*15*).

As the comet approaches the Sun, the overall temperature increases, and as the seasons change, there may be significant changes in the $H_2O$, CO, and $CO_2$ outgassing in the high $CO_2/H_2O$ ratio region in Figure 4. Observations at Hartley 2 were made when the comet was much closer to the Sun than 67P is now. Yet these observations were consistent with seasonal effects as well. It remains to be seen if, the seasonal effects suggested here persist with the increase in outgassing at the comet as 67P gets closer to the Sun in the coming months, especially near perihelion at 1.24 AU in summer 2015.

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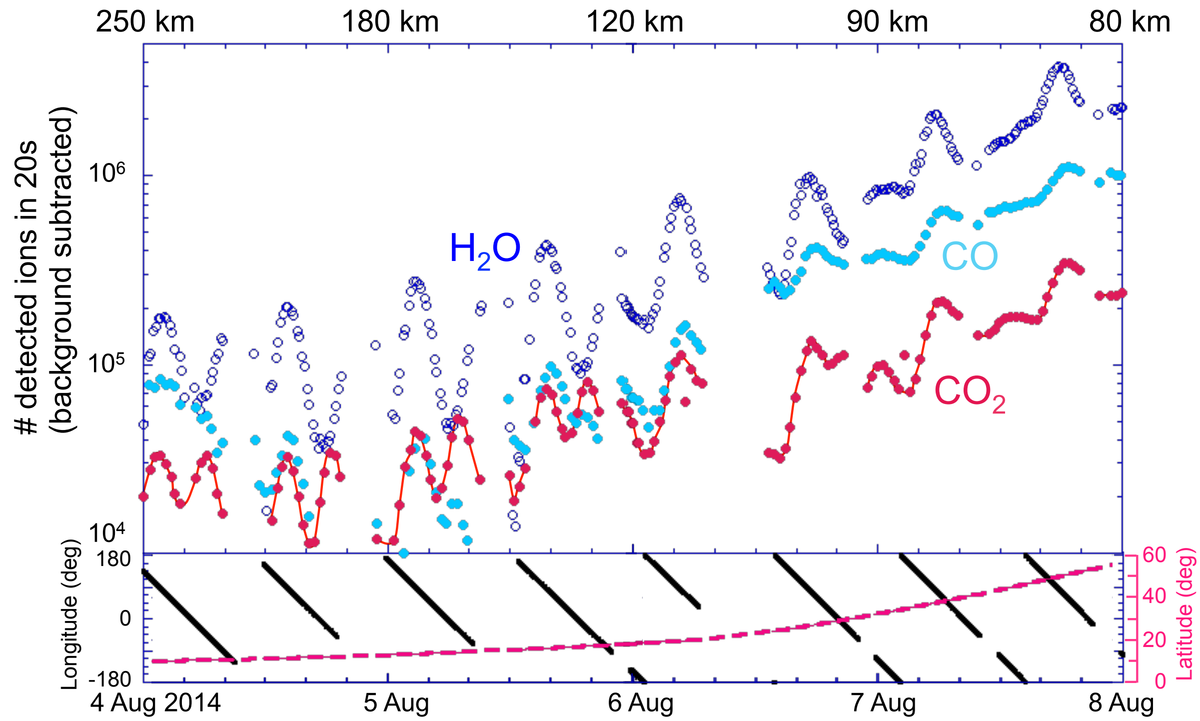


**Fig. 1**. The measured composition of the coma of 67P for the main species $H_2O$ (dark blue), CO (light blue), and $CO_2$ (red). The signal increases with decreasing distance to the comet, while superposed are diurnal variations. $CO_2$ has a different periodicity than $H_2O$.

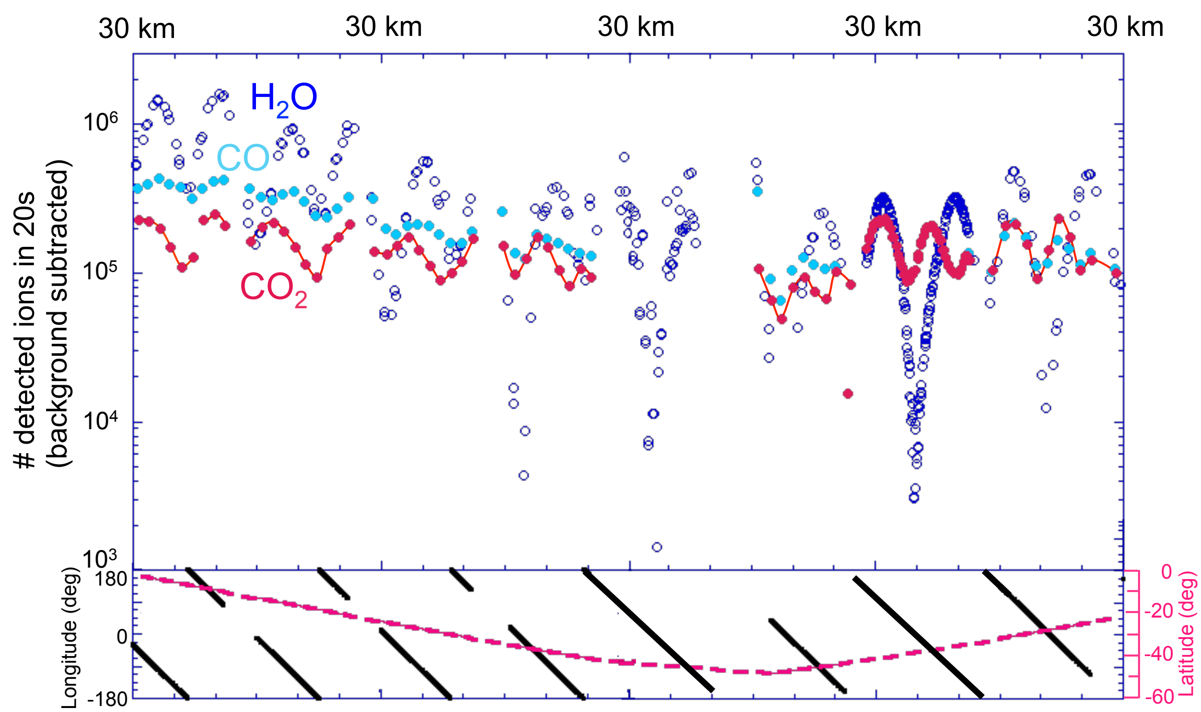

**Fig. 2.** $H_2O$ (dark blue), CO (light blue), and $CO_2$ (red) in the coma of 67P as a function of time. $H_2O$ and $CO_2$ have different periodicities and there are deep minima in the $H_2O$ signal. CO follows the $CO_2$ profile with less variation.

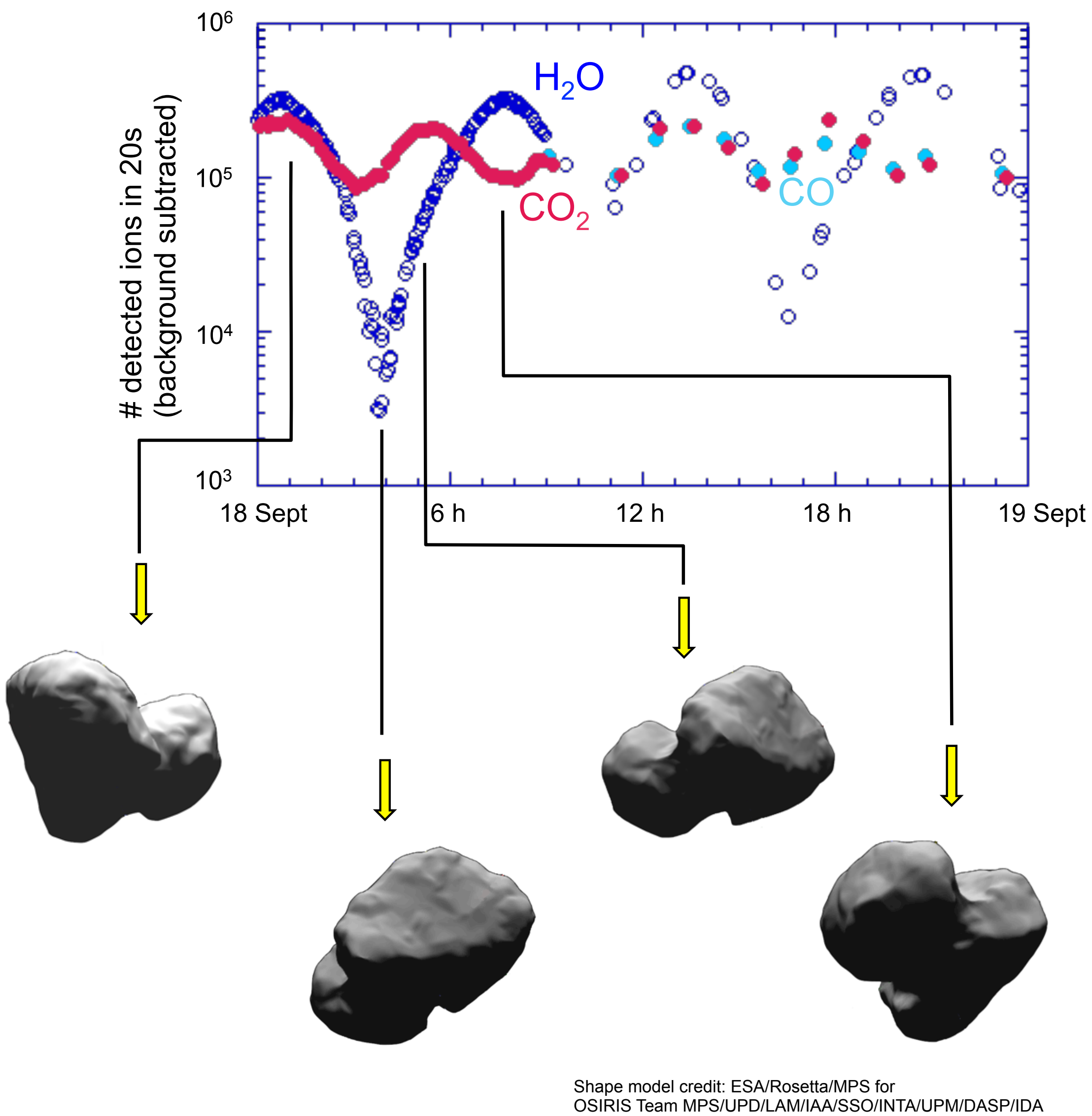


**Fig. 3.** $H_2O$, CO, $CO_2$ profiles for September 18, 2014. The snap shots of the spacecraft view of the comet show that $H_2O$ peaks are observed when the neck region is in view. The separate $CO_2$ peak and the deep minimum in $H_2O$ occur when the spacecraft views the larger of the two lobes and the neck region is blocked. (Shape model credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA).

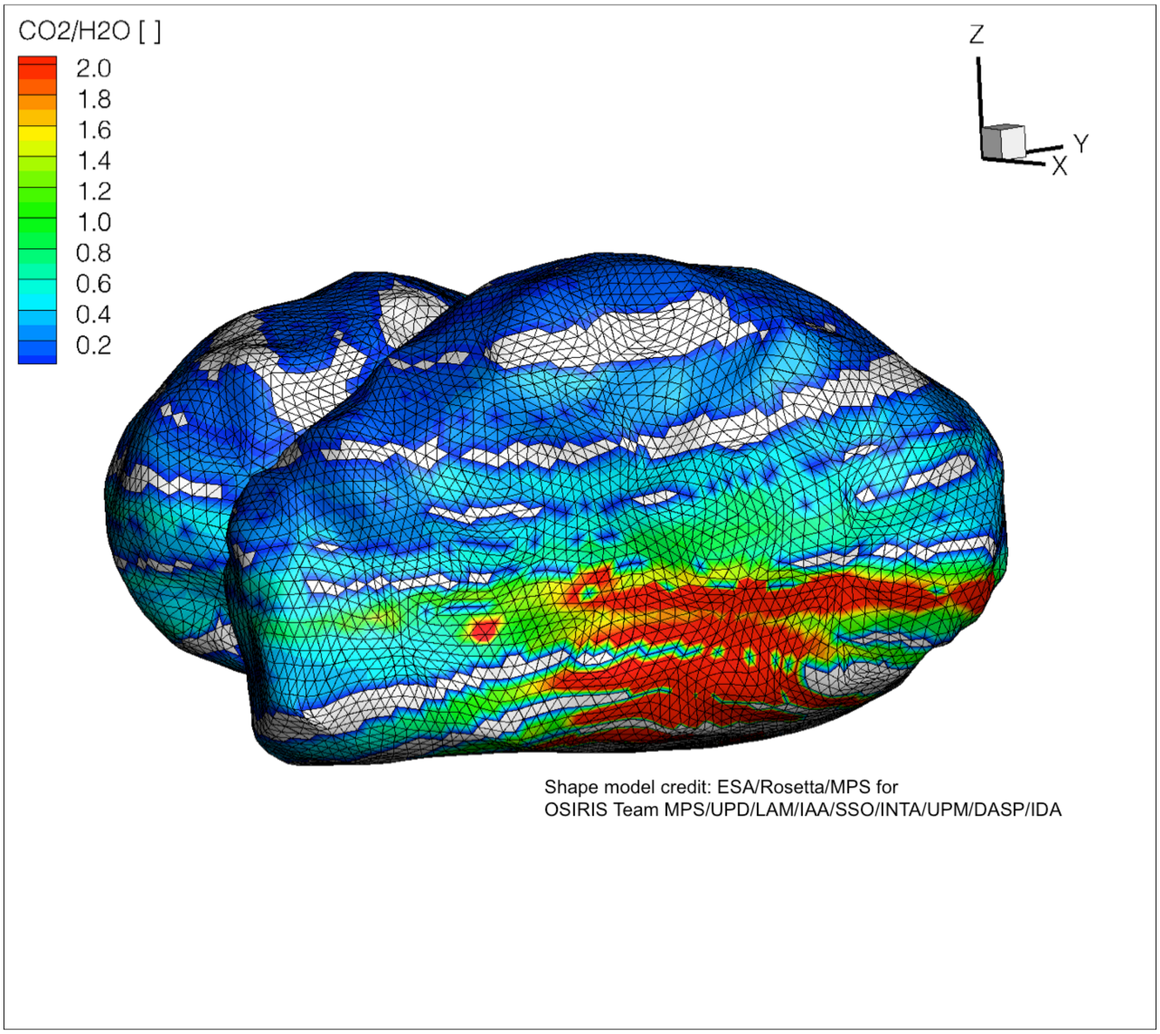


**Fig. 4.** The measured coma composition ratio of $CO_2/H_2O$, projected nadir on the comet. A high ratio is measured for the lower part that is poorly sunlit in northern hemisphere summer. (Shape model credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA).